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Investigations on the Plant Uptake of Fission Products from Contaminated Soils. I. Influence of Plant Species and Soil Types on the Uptake of Radioactive Strontium and Caesium

by

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Abstract

Results of pot experiments on the uptake of radioactive Sr and Cs by different plant species are presented, and comparisons are made between the uptake figures registered on some representative Danish soils. The uptake of radioactive Sr varied considerably between plant species and could be evaluated from their Ca uptake. The Sr-89/Ca ratio varied between different parts of the same plant, being relatively high in the roots of root crops and low in seeds and fruits. The Sr-89 uptake from different soil types decreased with increasing content of exchangeable Ca in the soils. The Cs-137 uptake varied between plant species and could be reduced by potassium fertilization. The uptake from different soil types generally decreased with increasing clay content, but also the content of organic matter influenced the plant availability of Cs-137.

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INTRODUCTION

The uptake of fission products by plants constitutes an important step in the movement of these elements from contaminated soils to human food. Many investigations (e.g. Jacobsen and Overstreet 1948, Klechkovsky and Guliakin 1957 and Romney et al. 1963) on the soil - plant relationships of different fission products have shown that the long-lived isotopes of strontium (Sr-90 and Sr-89) and caesium (Cs-137) are of special interest in this connection, and much work has been done to elucidate the behaviour of Sr and Cs in soil and their uptake by plants.

In assessing the hazards from contamination of agricultural areas by these isotopes it is very important to know the influence of such factors as the plant species, soil types, cultivation practices, liming, and mineral fertilization on the amount taken up by crops grown on contaminated soils. The present report gives results of pot experiments on the uptake of radioactive Sr and Cs by different plant species, and comparisons are made between the uptake figures recorded on some representative Danish soils.

MATERIALS AND METHODS

Soil Types

The soil samples used as growth media in the pot experiments were obtained from the ploughed layers of typical Danish agricultural soils. Some characteristics of the soils are given in table 1. The stable Sr- and Ca-contents are shown in table 2. The Sr is recorded as micro-equivalents (μeq) and the Ca as milli-equivalents (meq) per 100 g of air-dry soil. The Sr/Ca ratios did not vary much between the soils.

Prior to potting, the soils were enriched with the essential plant nutrients to ensure normal development of the plants. Sr-89 or Cs-137 in solutions was added to small samples (30 g) of the soils. These samples were air-dried and carefully mixed with the main portion of soil. The contaminated soil samples were transferred to PVC-pots containing from 0.8 to 1.0 kg depending on the soil type. In the experiments with different plant species somewhat larger pots containing 1.2 kg of soil no. 40 (table 1) were used.

Plant Species

Forty-four different plant species were tested. In table 3 the common name, botanical name, variety if specified, and time of harvest are given. Four pots of each species were seeded on May 17, 1962. Two of the pots contained soil contaminated with 3 μc carrierfree Sr-89, and the soil in the remaining two pots was contaminated with 10 μc carrierfree Cs-137 per pot.

For the investigation of the influence of soil types, red clover and rye grass were grown in all the soils listed in table 1.

Growing Conditions

After seeding the pots were placed on benches in the greenhouse and watered daily with deionized water. During the summer period the temperature was intended to be controlled between 18 and 25^{o}C, but on very hot days it may have risen to about 30^{o}C. In the cold season, autumn, winter and early spring, the temperature was maintained between 15 and 18^{o}C. Supplementary light from Philips fluorescent tubes (TLF W/33, approximately 100 watts per m^2) was applied from about October 15 until about March 15.

Analytical Procedures

On harvesting, the crops were cut to about 2 cm above the soil surface. The harvested material from each pot was dried for 18 hours at 80^{o}C, weighed, and milled. For each treatment, two 1.5 g samples of the plant powder were pressed into briquettes by hydraulic pressure. The briquettes were measured for radioactivity. The activity present at the time of counting was corrected for the decay of activity from the start of the experiments. The briquettes were dry-combusted after counting, and the ash solution was titrated with 0.01 M solution of the di-sodium salt of ethylene-diamine-tetra-acetic acid (EDTA) for determination of the Ca and Mg contents of the samples. K and Na were determined by flame photometry.

Strontium and calcium were extracted from soil samples with N ammonium acetate solutions and 2 N HCl. The extracted stable Sr was determined by flame photometry and Ca by titration against EDTA.

RESULTS AND DISCUSSION

The uptake of Sr and Cs by forty-four different plant species grown in soil No. 40 was measured in a pot experiment during the summer of 1962.

The investigations on the uptake from different soil types were performed as long-term pot experiments, and several harvests were made.

The Uptake by Different Plant Species

The cereal crops were harvested at the time of ear emergence and the grasses and clovers when the plants had grown to a height of about 25 cm. The beans, yellow lupin, rape, cabbage, white mustard, flax, and sunflowers were harvested at the time of flowering and the root crops and potatoes when the plants had produced sufficient material for the analysis. The vegetables were taken at the stages of growth at which they are normally harvested for human consumption. Only the above-ground part of the plants was harvested except in the case of root crops and potatoes.

Yield of dry matter and analytical data are given in table 4.

Strontium

Between plant species belonging to the same botanical family there was considerable variation in the concentration of Sr-89 in dry matter. On an average, however, the lowest concentration was found in the gramineae, an appreciably larger content of Sr-89 was found in most of the crucifers, and the highest concentration occurred in the legumes and the umbelliferae.

The Sr-89 content was larger in barley and rye than in wheat and oats. This agrees with the results reported by Evans and Dekker (1962) for the Sr-90 concentration in straw. But the difference between these plant species in the present investigation is greater than that reported by Evans and Dekker and also greater than that found in other experiments in our department in which the plants were grown to maturity. Possibly this is due to the difference in the physiological stage of growth at the time of harvest.

Among the grasses commonly used in agricultural practice the cock's foot has the lowest Sr-89 concentration in dry matter, while there is no difference between rye grass, timothy and meadow fescue. Approximately the same Sr-89 concentration was found in the 1st and the 2nd cut. Kidney vetch contains more Sr-89 per g of dry matter than the other legumes tested, but also in stems and leaves of common pea the concentration is high, whereas it is very low in the seeds of pea.

The Sr-89 content of different parts of the plants varies considerably. In root crops the highest Sr-89 concentration was found in the tops. The Sr-89 content of the mangold roots seems to be rather large, but the reason for this is likely to be the early stage of development at the time of harvest. Tomato fruits have a very low Sr-89 concentration, and the same is true of potato tubers.

The Sr-89 and Ca concentrations in the plants vary alike. The correlation coefficient between all the Sr-89 and Ca concentrations listed in table 4 was 0.90, and from the tables it will be seen that the Sr/Ca ratio varied from 0.5 to 4.1 μc Sr-89 per g Ca. The lowest values, Sr-89/Ca $<$ 1.5, were found in tomato fruits and seeds of pea, and Sr-89/Ca $>$ 3.0 was found only in the roots of root crops. This is in accordance with the results of Martin, Newbould and Scott Russell (1957), who found that the plants were able to discriminate against Sr relative to Ca during the translocation of these elements within the plants. As a consequence the Sr-89/Ca ratio decreases from root to top (seed and fruit).

The ratio between total Sr-89 and total Ca uptake (fig. 1) varied between 1.5 and 3.1, and the correlation coefficient increased to 0.98, indicating that discrimination against Sr-89 relative to Ca probably does not occur during the root uptake. The results of the present investigation agree very well with those of Frederiksson et al. (1958) and Evans and Dekker (1962), who stated that the root uptake of Sr-89 by different plant species could be evaluated from their Ca uptake.

Caesium

The plants absorb Cs-137 from contaminated soil to a much smaller extent than they do Sr-89. A comparison of the concentration factors (the ratios of activity per g of plant material to the activity per g of soil) showed concentration factors for Sr-89 ranging from 2 to 20 and for Cs-137 from 0.1 to 1.0 for the plant species used in the present experiment. The Cs-137 content varied greatly between plant species (table 4). The root crops tended to accumulate most Cs-137, but no botanical group could be characterized by an extremely high or low Cs-137 concentration.

Because of the chemical similarity between Cs-137 and K, the Cs-137 uptake from contaminated soil is often related to the K-uptake. From the Cs-137/K ratios in the plant materials presented in table 4 it will be seen that no constant relationship could be observed when different plant species were grown in a contaminated soil. Also the total uptake of Cs-137 seems to vary independently of the K-uptake as shown in fig. 2. However, the analyses of the 1st and 2nd cuts of the grasses (table 4) indicate a relationship between Cs-137- and K-uptake. The Cs-137 concentration increased markedly from 1st to 2nd cut, whereas the K concentration in the plant material decreased. These results agree with those obtained by Nishita et al. (1958 and 1960), who showed that when the soil K was reduced by cropping, the plant uptake of Cs-137 increased. From the present experiment it may be assumed that the relative absorption of Cs-137 and K does not depend as much on the plant species as on the soil chemistry determining the relative availability of these two elements.

Influence of Soil Type

Rye grass and red clover were grown as test plants in these investigations. Five replicates were used, and successive cuts were taken at appropriate stages of development. The yield of dry matter was determined for each pot while the chemical and radiochemical analyses were made on a composite sample made up by mixing the plant material from the five replications.

Strontium

The Sr-89 uptake from different soil types receiving either none or 1 g $CaCO_3$ per kg of soil (2 meq/100 g) was measured. The soils were contaminated with 25 μc carrierfree Sr-89 per kg. The experiment commenced in September 1960, and the plants were grown in the greenhouse for 11 months, during which period six harvest were made. After the 2nd cut the rye grass was supplied with 100 mg N and 280 mg K per pot (added as a 10 ml solution of KNO_3), and after each of the following cuts 100 mg N was added per pot (10 ml solution of NH_4NO_3). The red clover received additional K and P (340 mg KH_2PO_4 per pot) after the 5th cut.

Summaries of the total yield of dry matter, the Sr-89 uptake and the average content of Sr-89 for the six cuttings are given in table 5. The yield of dry matter was not significantly influenced by the addition of 1 g $CaCO_3$ per kg soil, but the Sr-89 uptake was on an average reduced. However, this reduction was not very great, possibly because of the rather small amounts of $CaCO_3$ added. Some variation in Sr-89 concentration was observed during the growing period. It may have been caused by changes in the growing conditions (temperature, light), but also a difference in stage of development at the time of cutting may have influenced the results.

Fig. 3 shows the relationship between the average Sr-89 concentration of the crops and the exchangeable Ca of the soils. The concentration of Sr-89 decreases in both species with increasing content of exchangeable Ca in the soil. The concentration is 2 - 3 times higher in red clover than in rye grass, which is also shown in table 5.

The Ca and Mg contents and the Sr-89/Ca ratios in the first crops of rye grass and red clover are given in table 6, and fig. 4 shows the ratios as a function of the exchangeable Ca in the soils. The ratios are approximately equal for rye grass and red clover grown on the same soil. In general, the Sr-89 concentration and the Sr-89/Ca ratio of the plants decrease with increasing content of exchangeable Ca in the soil. Considerable differences, however, are found for crops grown on different soils containing equal amounts of exchangeable Ca. These differences might be due to variations between the soils in plant availability of the exchangeable Ca as determined by extraction with N ammonium-acetate (table 1). Furthermore, the relative availabilities of Sr and Ca are influenced by the cation-exchange capacity (clay and humus content) and the degree of Ca saturation (Frederiksson et al. 1958 and 1961). The majority of the soils used in the present experiment contained between 6 and 18 meq Ca per 100 g soil, and the Sr-89 content in the crops from these soils varied by a factor of about 5; the variation was generally in accordance with that of the Ca content, but also other soil characteristics influenced the results, apparently most when the soil had a rather low concentration of exchangeable Ca.

The present investigation clearly demonstrates that the Sr concentration in crops grown on contaminated soils varies appreciably. This variation is mainly due to the difference between soils in content of plant-available Ca, but also other soil characteristics may be considered in evaluating the consequences of radioactive contamination of agricultural areas.

Caesium

Measurements were made of the Cs-137 uptake from twenty-two different soil types with 10 μc Cs-137 per kg. An investigation of the influence of carrier Cs and two methods of contamination was also made. The uptake by rye grass was measured in soils to which the Cs-137 had been supplied by the following methods:

1. Carrierfree Cs-137 was added in solution to 30 g of soil, which was then air-dried and carefully mixed into the bulk of soil.

2. Cs-137 solution containing 8 mg carrier Cs per mc Cs-137 was added in the same way as mentioned above (1).

3. Cs-137 solution containing 8 mg carrier Cs per mc Cs-137 was added to 30 g quartz sand, which was then air-dried and mixed into the soil.

The uptake by red clover was only measured in soils contaminated with carrierfree Cs-137 (method 1).

The experiment commenced in February 1962, and the plants were grown in the greenhouse for approximately 20 months, during which period 15 harvests were made of the red clover and 17 harvests of the rye grass. After each cutting, until the thirteenth (June 27, 1963), the rye grass was supplied with 100 mg N per pot, usually in the form of NH_4NO_3 solution, but after the 4th and the 8th cut KNO_3 solution was used, and the influence of added K was elucidated in the following cuts. The comparison of different methods of contamination (1, 2 and 3) was concluded after the 8th cut, and to the pots given treatments 2 and 3 was then added 100 mg N in the form of $Ca(NO_3)_2$ and $Mg(NO_3)_2$ respectively. In this way it was possible to use the 9th cut to compare the influence of KNO_3, $Ca(NO_3)_2$ and $Mg(NO_3)_2$ on the uptake of Cs-137. To the red clover was added KNO_3 (277 mg K per pot) after the 4th cut, and the plants were then allowed to exhaust the soils of plant nutrients.

Summaries of the total yield of dry matter, the Cs-137 uptake and the average uptake of Cs-137 per g of dry matter are given in table 7 for the treatments using carrierfree Cs-137 (method 1). The Cs-137 uptake varied very much between soil types. An extremely high Cs-137 concentration was found in crops from the very light sandy soil no. 29 (indicated by dashed lines in fig. 5). The Cs-137 content in crops from the different soils in general decreased with increasing clay content in the soils. But some discrepancies from this general trend indicate that also other factors influence the plant availability of Cs-137. The uptake from soil no. 34 was rather large compared with the general trend. This may partly be explained by the relatively large content of organic matter in that soil (table 1). According to the results of Barber (1964) and Frederiksson and Eriksson (1966), the Cs-137 uptake is much larger from organic than from mineral soils. Another factor that might influence the variability in uptake of Cs-137 is differences in the types of clay minerals in the soils.

Both the dry-matter production and the Cs-137 uptake varied appreciably during the period of growth. The accumulated dry-matter production and the Cs-137 contents in the crops as functions of time are shown in figs. 6-9. For convenience in presenting the results, the soils were grouped according to their clay content and designated as loamy sand (clay $<$ 9.0%), sandy loam (clay 9.0 - 15.8%), and sandy clay loam (clay $>$ 15.9%). The peat soil (no. 14) was grouped together with the sandy loams, and the results from the extremely light sandy soil no. 29 were omitted in these comparisons.

About 50% of the total yield of dry matter was obtained from the first six cuttings (figs. 6 and 7). During that period there was not very much difference in yield between the various soils. No. 14, however, was the most productive of the soils used. As the soil exhaustion of mineral nutrients continued, the productivity (dry-matter production per day) decreased and the differences between soil types became more pronounced. Some indications of seasonal variation can also be seen from the curves. The productivity decreased during autumn and winter (from the 6th to the 10th cut of rye grass), and a slight increase was observed during the spring and early summer of the second year of growth. But after about 500 days of growth the soils were so depleted of nutrients that the growth almost ceased.

Fig. 8 shows the Cs-137 concentration in rye grass grown in different soils and the variation during the growing period. The difference between crops from the three groups of soil types is clearly demonstrated, and also within each group of soil the variation is appreciable. The general trend of the Cs-137 concentration in rye grass versus time is a very great increase from the 1st to the 4th cut and then a smaller concentration in the 5th and 6th crops followed by a moderate increase until the 8th crop. After the 8th cutting the Cs-137 concentration decreased appreciably for the following three crops; then it again increased until the 14th cut, and in the last three crops a decreasing concentration was observed. This general trend clearly shows the interaction between K and Cs-137 and indicates an important influence of N. As mentioned above, the soils were supplied with KNO_3 after the 4th and 8th cuttings (points indicated by arrows on the abscissa of fig. 8), and the response was a very effective reduction in the Cs-137 uptake. The results agree very well with those reported by Nishita et al. (1960), who showed that K-fertilization reduced the Cs-137 uptake from soils depleted in native K by cropping. The decreased Cs-137 uptake observed for the last three crops could not be explained as an effect of K, but may perhaps have been caused by the change in N supplied after the 13th cut, when no more N was added.

Also for the red clover (fig. 9) the influence of K on the Cs-137 uptake was clearly demonstrated. Potassium was added only after the 4th cut, and a very great reduction in Cs-137 concentration was observed in the 5th crop. After the 5th crop a general increase in the Cs-137 concentration was found until the 10th crop. From that time a deviation from the general trend was observed. The Cs-137 content in crops from some of the most productive soils (sandy clay loams) continued to increase, whereas the content decreased in crops from other soils. In general the difference between soils increased. The cause of these effects could not be proved by the present experiment, but it might be differences in the extent to which the soils were exhausted of plant nutrients.

The K content of red clover (fig. 10) was very large in the 1st crop, but decreased to a very low figure in the 4th crop. Addition of KNO_3 was followed by increased K concentration in the 5th crop, and then a steady decrease was observed until about the five hundredth day of growth, from which a tendency to increased K concentration was noted for the remaining part of the growing period. The variation in K content corresponds very closely to the variation in Cs-137 content. When the K content decreases, the Cs-137 content increases and vice versa. It follows that a very great variation is to be found in the Cs-137/K ratios in crops. The value of this ratio as an indicator of the Cs-137 contamination is rather doubtful as compared with that of the Sr-90/Ca ratio as a measure of the Sr-90 contamination.

Influence of carrier Cs and method of contamination. The effects of the three different methods of Cs-137 application were measured in eight successive cuts of rye grass. Table 8 shows summaries of the results. The various treatments did not influence the production of dry matter. But the small amount of carrier Cs added in treatments 2 and 3 increased the Cs-137 uptake by about 20%. This is in accordance with the results obtained by Frederiksson et al. (1958) and Nishita et al. (1962). Using a somewhat higher carrier concentration than that used in the present experiment, they found a very marked increase in the plant uptake of Cs-137. The comparison between treatment 2 (Cs-137 solution added to small soil samples before being mixed with the bulk) and treatment 3 (Cs-137 added to quartz sand) did not show any difference in Cs-137 content in the crops.

Influence of KNO_3, $Ca(NO_3)_2$ and $Mg(NO_3)_2$. After the 8th cutting of rye grass, the pots given treatment 1 were supplied with 100 mg N per pot in KNO_3 solution and those given treatments 2 and 3 with equivalent amounts of N in $Ca(NO_3)_2$ and $Mg(NO_3)_2$ respectively. In table 9 the Cs-137 concentrations in the 8th and 9th crops are given. It should be emphasized that the figures for $Ca(NO_3)_2$ and $Mg(NO_3)_2$ in the table are not strictly comparable with those for KNO_3 as about 20% less Cs-137 was absorbed in the foregoing 8 cuts. However, it may be assumed from the results obtained that the interaction of $Ca(NO_3)_2$ and $Mg(NO_3)_2$ with the Cs-137 uptake is very small compared with the effect of KNO_3.

CONCLUSIONS

The plant uptake of radioactive Sr varies considerably between species and is closely correlated with the Ca uptake. The uptake of Sr-89 by different plant species can be evaluated from knowledge of their Ca uptake. The Sr-89/Ca ratio varies between different parts of the same plants, probably owing to discrimination against Sr relative to Ca during the translocation within the plants. The ratio is relatively high in the roots of root crops and relatively low in seeds and fruits.

The Sr-89 uptake from different soil types is closely related to the content of exchangeable Ca in the soils. However, some deviations from this general trend indicate that the exchangeable Ca does not reflect the true availability of the soil Ca. Other soil factors may influence the relative availability of Sr and Ca.

Also the Cs-137 uptake varies appreciably between plant species, but no characteristic relation could be found for the Cs-137 and K contents of plants grown in soils abundantly supplied with K. However, when the soils were depleted of K by successive croppings, the Cs-137 content of the plants increased, and addition of K to such soil caused an important reduction in the Cs-137 uptake. The uptake from different soil types generally decreased with increasing clay content, but also the type of clay and the content of organic matter in the soil may be assumed to influence the results.

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Table 1

Characteristics of the soils used in the pot experiments

Soil no.	Locality	Soil type	Particle size in mm, % > 2.0	2.0-0.1	0.2-0.02	0.02-0.002	< 0.002	Content of organic matter %	Cation-exchange capacity mg/100 g	Base saturation %	pH (H_2O)	$CaCO_3$ %
2	Faarevejle	sandy loam	0.0	3.4	73.8	4.2	15.8	2.8	22.4	95	7.6	2.5
4	Frederiks	loamy sand	3.6	35.9	39.2	7.6	8.0	5.7	26.4	41	6.0	-
6	Højgaard	sandy loam	[illegible].1	28.3	49.4	6.0	9.4	3.8	19.7	37	6.0	-
8	Vinkel	sandy loam	4.1	21.7	49.7	8.4	13.7	2.4	17.5	74	7.2	-
9	Aarup	sandy clay loam	0.0	8.1	49.7	13.3	28.1	2.8	19.2	49	5.8	-
10	Ørum	sandy loam	2.3	26.2	49.8	7.0	11.8	2.9	16.6	66	7.1	-
11	Vejrum	loamy sand	3.7	41.3	37.3	6.6	6.0	5.1	23.7	30	5.6	-
13	Risö I	sandy clay loam	0.8	17.0	50.1	8.7	21.3	2.1	17.3	89	7.4	-
14	Lammefjord	muck	0.0	2.4	32.7	21.5	30.6	12.8	47.4	94	7.6	6.1
15	Jyndevad	loamy coarse sand	0.7	53.2	36.5	3.2	4.3	2.1	12.2	44	6.7	-
18	Ellishøj	calcareous clay loam	0.1	19.6	49.3	6.5	21.0	3.5	26.4	93	8.0	12.7
23	Borris	loamy sand	0.0	30.8	50.2	6.8	9.0	3.2	15.1	26	5.9	-
25	Borris	loamy sand	0.0	31.9	50.5	5.9	6.1	3.6	16.3	33	5.9	-
28	Borris	loamy sand	0.5	31.2	50.7	5.6	6.2	5.6	17.6	33	6.0	-
29	Tarm	sand	0.5	69.1	21.1	2.5	3.9	2.9	18.0	7	4.8	-
34	Åstrup	calcareous clay loam	0.6	7.1	44.9	18.1	27.1	5.2	22.8	89	7.9	44.7
33	Spangsbjerg	sandy loam	0.8	27.1	51.8	6.0	12.2	2.1	13.4	64	7.0	-
36	Ødum	sandy clay loam	0.5	15.0	56.5	8.5	18.9	2.6	14.2	72	7.3	-
37	Askov	sandy loam	1.3	33.0	45.4	5.9	12.5	1.9	11.6	51	7.2	-
38	Blangstedgård	sandy clay loam	2.4	23.8	48.4	7.5	15.9	2.0	13.5	58	6.8	-
39	Risö II	sandy clay loam	0.8	17.1	53.2	10.5	16.3	2.1	11.4	76	7.1	-
40	Lille Valby	loamy sand	0.0	15.0	67.5	5.7	9.0	2.6	15.2	92	5.7	-

Table 2

Strontium and calcium contents in the soils extracted by $\underline{N}$ ammonium acetate and $2\underline{N}$ hydrochloric acid

Soil no.	µeq Sr/100 g soil		meq Ca/100 g soil		µeq Sr/meq Ca	
	NH_4-Ac	HCl	NH_4-Ac	HCl	NH_4-Ac	HCl
2	21.9	93.6	16.8	67.0	1.3	1.4
4	14.3	25.6	11.6	16.3	1.2	1.6
6	10.0	18.0	8.2	11.8	1.2	1.5
8	15.0	20.5	12.1	16.0	1.2	1.3
9	15.2	21.2	10.0	12.4	1.5	1.7
10	11.6	24.9	11.8	16.6	1.0	1.5
11	10.7	16.4	7.5	9.8	1.4	1.7
13	20.5	29.9	15.5	23.7	1.3	1.3
14	60.7	200.9	38.0	162.4	1.6	1.2
15	5.5	7.5	5.1	6.6	1.1	1.1
18	33.3	220.9	22.1	184.3	1.5	1.2
23	5.9	6.8	4.1	4.9	1.4	1.4
25	8.4	9.4	5.4	6.6	1.6	1.4
28	8.6	13.7	5.8	7.2	1.5	1.9
29	-	-	0.3	0.6	-	-
34	29.0	419.7	25.4	918.4	1.1	0.5
35	7.5	10.3	6.4	8.8	1.2	1.2
36	14.1	17.1	9.2	13.3	1.5	1.3
37	7.5	7.5	5.7	7.1	1.3	1.1
38	8.0	8.4	6.9	9.1	1.2	0.9
39	11.4	16.9	9.8	11.7	1.2	1.4
40	6.4	8.2	4.4	5.6	1.5	1.5

Table 3

Plant species, varieties and dates of harvest. (The seeds were sown on May 17th, 1962)

Species	Variety	Date of harvest
Gramineae		
Barley (Hordeum sativum)	Freja	June 26
Oats (Avena sativa)	Stål	" 27
Spring wheat (Triticum vulgare)	Svenno	" 27
Spring rye (Secale cereale)	Petkus	" 30
Maize (Zea maize)	Canada Cross	" 27
Rice (Oryza sativa)	-	July 18
Common millet (Panicum miliacium)	-	" 18
Perennial rye-grass (Lolium perenne)	Øtofte Dux III	June 26 and July 18
Cock's-foot (Dactylis glomerata)	Pajbjerg II	" 26 " " 18
Timothy (Phleum pratense)	Øtofte A III	" 25 " " 18
Meadow fescue (Festuca pratensis)	Øtofte II	" 25 " " 18
Leguminosae		
Red clover (Trifolium pratense)	Dalmfeldt Monarch IV	July 18
White clover (Trifolium repens)	Morsø Øtofte II R	" 18
Alsike clover (Trifolium hybridum)	Øtofte II	" 6
Common bird's-foot trefoil (Lotus corniculatus)	Øtofte II	" 11
Kidney vetch (Anthyllis vulneraria)	Roskilde 103	" 18
Lucerne (Medicago sativa)	Du Puits	" 11
Common vetch (Vica sativa)	Øtofte	June 27
Common pea (Pisum sativum)	Kelvedon Wonder	July 6
Kidney bean (Phaceolus vulgaris)	-	6
Yellow lupin (Lupinus luteus)	Pajbjerg 515	" 6
Cruciferae		
Rape (Brassica napus olifera)	Svalöf Regina	June 30
Cabbage (Brassica oleracea)	Rothwell	July 18
Swedes (Brassica napus var. rapifera)	Wilhelmsburger XI, F	" 18
Radish (Raphanus sativus var. radicula)	-	June 20
White mustard (Sinaplis alba)	-	" 20
Horse-radish (Armoracia rusticana)	-	July 18
Umbelliferae		
Carrot (Daucus carota)	James, Roskilde X	August 7
Celery (Apium graveolens)	Alabaster	September 13
Garden chervil (Anthriscus cerefolium)	-	July 6
Parsley (Petroselirum crispum)	-	" 6
Dill (Anethum graveolens)	-	" 6
Other botanical families		
Onion (allium cepa)	-	August 7
Leek (Allium porrum)	-	July 18
Chives (Allium schoenoprasum)	-	" 18
Mangold (Beta vulgaris)	Øtofte Nova XII	August 7
Beetroot (Beta vulgaris var. rubra)	Detroit No. 343	" 7
Spinach beet (Beta vulgaris var. cicta)	-	July 18
Tomato (Lycopersicum esculentum)	Danish Export	August 7
Tobacco (Nicotiana tabacum)	Virginia	July 18
Potato (Solanum tuberosum)	Bintje	" 18
Flax (Linum usitatissimum)	-	June 26
Hemp (Cannabis sativa)	-	July 6
Sunflower (Helianthis annuus)	-	" 6

Table 4

Yield of dry matter, radioactivity and mineral content in different plant species

Plant species	Yield, g/pot	Sr-90 mμc/g	Content in dry matter			K mg/g	Sr-90 / Ca m/g	Cs-137 / K mμc/g
			Cs-137 mμc/g	Ca mg/g	Mg mg/g			
Gramineae								
Barley	6.4	2.12	0.60	2.07	0.81	33.6	1.0	15
Oats	13.4	4.90	1.85	2.67	1.07	31.8	1.9	61
Spring wheat	11.2	5.41	0.30	2.17	0.66	30.3	2.5	12
Spring rye	6.7	10.00	0.67	3.92	1.15	31.6	3.0	21
Maize	20.6	7.57	0.83	3.90	1.54	21.4	1.9	39
Rice	3.5	8.14	0.19	5.76	2.17	34.0	1.8	77
Millet	15.8	8.11	1.47	2.73	1.70	16.6	2.9	88
Rye-grass, 1. cut	3.6	13.02	0.66	7.68	1.31	29.5	1.7	23
" " 2. cut	4.7	12.68	3.37	7.13	3.86	16.7	1.8	202
Cock's-foot, 1. cut	5.8	8.07	1.23	4.41	1.76	32.7	2.0	38
" " 2. cut	4.0	8.66	8.71	4.30	3.07	13.6	2.0	640
Timothy, 1. cut	5.5	14.80	0.68	5.38	1.33	28.9	2.6	23
" 2. cut	4.8	14.10	3.31	5.36	1.03	19.4	2.7	171
Meadow fescue, 1. cut	4.9	13.86	0.57	7.04	1.70	33.8	2.0	17
" " 2. cut	4.0	13.41	3.03	7.93	4.12	18.6	1.0	163
Leguminosae								
Red clover	21.3	29.27	1.86	15.50	1.61	10.8	1.9	173
White clover	20.5	29.00	2.61	16.00	1.30	12.0	1.7	218
Alsike clover	16.7	26.57	3.38	14.70	1.42	18.8	1.7	180
Bird's-foot trefoil	16.9	25.54	3.36	13.30	2.30	17.3	1.8	194
Kidney vetch	7.3	50.12	1.08	23.30	3.67	21.4	2.5	51
Lucerne	6.7	28.41	2.15	14.40	1.02	18.7	2.0	115
Common vetch	14.0	23.50	3.77	13.30	1.36	17.5	1.6	215
Common pea, seed	2.0	1.57	0.81	1.26	1.16	13.0	1.2	69
Common pea, pod	2.9	28.07	0.84	11.10	2.04	13.1	2.4	64
Common pea, leaves and stem	4.2	49.46	1.37	23.00	4.34	18.5	2.1	74
Bean	4.0	34.87	0.45	17.10	3.40	18.7	2.0	24
Yellow lupin	12.3	20.26	1.83	10.50	2.23	17.3	1.9	106
Cruciferae								
Rape	3.1	22.90	0.90	11.50	1.80	31.7	2.0	30
Cabbage	12.9	36.13	5.57	13.10	1.84	15.0	2.6	360
Swedes (roots)	3.4	12.71	4.02	3.67	1.74	16.4	3.5	294
Swedes (leaves)	3.0	30.01	7.87	17.40	1.12	14.0	1.9	486
Radish (roots)	2.2	15.26	1.40	4.64	1.04	30.9	3.3	45
Radish (leaves)	2.4	37.83	3.30	17.70	3.32	36.1	2.1	84
White mustard	6.3	18.76	2.87	10.10	0.80	30.2	2.0	96
Horse-radish (roots)	3.0	15.21	1.60	5.48	1.47	17.0	3.0	90
Horse-radish (leaves)	17.3	14.14	1.46	9.10	1.71	13.4	1.5	109
Umbelliferae								
Carrot (roots)	7.3	11.01	3.76	3.38	1.04	8.96	3.4	420
Carrot (leaves)	3.0	54.36	7.50	36.10	3.34	17.0	2.0	447
Celery (roots)	1.8	18.41	1.26	5.70	2.78	18.7	3.2	67
Celery (leaves)	3.1	40.83	3.06	24.00	3.06	37.2	1.7	83
Garden chervil	18.1	41.97	1.30	19.80	1.70	17.6	2.1	73
Parsley	5.4	23.63	2.66	11.60	3.44	36.3	2.1	76
Dill	11.7	15.81	1.10	8.06	1.90	23.0	1.9	48
Other botanical families								
Onion (bulbs + roots)	2.6	13.39	0.27	5.60	1.23	18.2	2.4	15
Onion (leaves)	1.3	26.56	1.48	17.70	1.83	39.8	1.5	37
Leek	6.0	18.03	0.84	11.70	2.70	27.4	1.5	31
Chives	5.2	18.71	0.94	12.40	1.11	29.3	1.5	35
Mangold (root)	2.7	26.96	1.80	6.60	1.78	11.0	3.8	171
Mangold (leaves)	3.6	62.31	6.76	21.10	5.79	27.0	3.0	250
Beetroot (roots)	2.3	17.48	2.87	4.29	1.40	13.3	4.1	228
Beetroot (leaves)	6.0	66.10	10.70	30.30	10.30	38.3	3.0	274
Spinach beet	4.5	32.88	3.65	15.70	4.09	20.6	2.1	178
Tomato (fruit)	2.3	4.40	3.80	8.91	0.77	25.0	0.5	40
Tomato (leaves)	0.9	23.40	1.14	11.00	1.93	13.3	2.0	86
Tobacco	6.6	61.30	0.75	19.46	4.05	32.6	3.2	23
Potato (tubers)	30.7	1.33	1.11	0.74	0.75	14.8	1.7	78
Potato (leaves + stems)	4.4	50.73	1.80	24.70	5.60	13.6	2.1	142
Flax	11.3	18.71	0.76	5.15	1.65	26.5	3.2	27
Hemp (stems)	4.5	25.98	3.00	8.80	1.07	12.8	2.9	160
Hemp (leaves)	8.0	43.35	3.87	25.70	3.40	18.9	1.7	205
Sunflower (stems)	10.3	10.80	0.48	4.05	1.36	6.80	2.7	77
Sunflower (leaves)	5.3	24.84	1.33	19.30	2.02	24.0	1.3	56

Table 5

Total yield of dry matter, Sr-89 uptake and average Sr-89 concentration in rye-grass and red clover from pot experiment with 20 soils with and without addition of $CaCO_3$. (25 μc Sr-89 per kg soil)

Soil no.	$CaCO_3$ added meq/100 g soil	Dry matter g/pot		Sr-89 uptake μc/pot		Average Sr-89 concentration mμc/g d.m.		Sr-89 concentration red clover/rye-grass
		Rye-grass	Red clover	Rye-grass	Red clover	Rye-grass	Red clover	
2	0	20.5	38.8	1.30	6.43	63.2	166	2.6
"	2	20.7	38.3	1.33	6.25	64.0	163	2.5
4	0	23.3	36.9	1.19	6.52	51.1	177	3.5
"	2	23.6	34.4	1.18	5.38	49.8	156	3.1
6	0	21.9	32.1	1.65	7.23	75.3	225	3.0
"	2	22.7	32.2	1.50	6.22	66.0	193	2.9
8	0	24.9	38.8	1.40	6.69	56.1	172	3.1
"	2	24.5	38.4	1.41	5.84	57.6	152	2.6
9	0	24.4	38.0	1.59	7.90	65.3	208	3.2
"	2	24.2	37.0	1.34	6.57	55.3	178	3.2
10	0	24.7	37.1	1.17	5.56	47.4	150	3.2
"	2	25.7	38.0	1.15	5.24	44.7	138	3.1
11	0	22.2	33.7	1.71	8.05	77.0	239	3.1
"	2	23.0	33.9	1.54	7.28	67.1	215	3.2
13	0	20.4	45.7	1.00	5.85	48.8	128	2.6
"	2	20.7	45.8	1.07	4.72	51.8	103	2.0
14	0	22.3	48.3	0.52	2.22	23.5	46	2.0
"	2	22.9	50.7	0.47	2.72	20.4	54	2.6
15	0	21.7	31.8	1.79	8.18	82.5	257	3.1
"	2	21.7	33.6	1.49	6.95	68.6	207	3.0
18	0	22.1	35.9	1.88	8.92	85.2	249	2.9
"	2	22.0	40.8	1.62	9.28	73.4	228	3.1
23	0	21.4	34.2	2.45	10.25	114.6	300	2.6
"	2	22.8	34.1	2.17	9.42	95.1	276	2.9
25	0	23.2	36.1	2.12	9.18	91.5	254	2.8
"	2	23.4	36.2	1.94	7.98	82.7	221	2.7
28	0	22.2	40.4	0.91	4.59	40.8	113	2.8
"	2	21.3	38.8	0.89	4.15	41.9	107	2.6
29	0	17.7	28.4	2.18	9.26	122.9	326	2.7
"	2	17.3	27.3	2.46	9.21	142.1	337	2.4
34	0	26.9	41.4	0.63	2.57	23.5	62	2.6
"	2	26.0	40.5	0.64	2.70	25.0	67	2.7
35	0	21.2	39.6	1.25	5.45	59.1	138	2.3
"	2	22.3	40.7	1.33	6.50	59.8	160	2.7
36	0	21.7	35.4	1.16	5.86	53.5	165	3.1
"	2	21.9	42.2	1.14	5.26	51.8	125	2.4
37	0	20.7	35.9	1.90	9.00	91.9	251	2.7
"	2	21.3	33.8	1.58	7.21	74.2	213	2.9
38	0	19.4	49.6	1.30	8.63	67.2	174	2.6
"	2	20.4	53.9	1.24	7.10	60.8	132	2.2

Table 6

Calcium and magnesium concentrations and Sr-89 to Ca ratios in the 1st crops of rye-grass and red clover from pot experiment with 20 soils with and without addition of $CaCO_3$

Soil no.	Ca added meq/100 g soil	Rye-grass mg per g dry matter Ca	Rye-grass mg per g dry matter Mg	µc Sr-89 per g Ca	Red clover mg per g dry matter Ca	Red clover mg per g dry matter Mg	µc Sr-89 per g Ca
02	0	8.84	0.87	7.1	32.0	5.66	7.2
"	2	7.87	1.09	7.9	30.9	3.87	7.0
04	0	9.45	1.02	6.3	32.2	4.91	6.7
"	2	9.40	1.04	6.2	32.9	6.45	6.6
06	0	8.41	0.75	9.0	31.2	6.47	10.2
"	2	8.25	1.27	8.0	33.7	5.69	7.9
08	0	9.19	1.35	7.7	33.3	4.76	8.3
"	2	9.05	1.65	8.5	32.3	4.73	7.4
09	0	6.37	1.29	9.6	28.3	6.63	10.0
"	2	6.95	1.71	8.8	29.9	5.78	7.8
10	0	8.76	1.40	6.6	28.7	4.68	6.8
"	2	9.45	1.42	6.2	32.5	3.85	5.8
11	0	7.97	1.76	10.1	29.8	5.71	10.7
"	2	8.18	1.31	8.9	31.5	5.53	8.9
13	0	11.10	1.11	5.1	31.8	6.39	5.7
"	2	11.30	1.74	5.7	32.7	5.12	4.4
14	0	9.00	1.57	2.6	26.5	6.10	1.8
"	2	8.25	1.78	2.7	25.6	5.83	2.0
15	0	5.66	1.25	14.0	27.7	6.62	12.2
"	2	6.98	0.90	11.2	28.1	9.54	8.9
18	0	7.19	1.85	13.5	19.7	6.53	15.2
"	2	7.28	1.50	11.1	24.9	7.23	11.3
23	0	5.75	1.59	20.5	26.1	7.62	19.2
"	2	6.44	1.52	16.3	27.9	7.19	15.5
25	0	6.71	1.64	14.5	23.4	5.36	14.5
"	2	7.81	1.54	11.7	25.5	6.62	11.8
28	0	10.70	1.56	4.8	35.4	6.28	4.2
"	2	10.40	1.38	5.0	36.4	5.10	3.9
29	0	7.42	1.58	17.1	32.7	8.58	15.0
"	2	7.81	1.55	19.7	31.9	8.24	15.1
34	0	11.60	1.58	2.6	36.6	9.14	2.5
"	2	12.00	1.72	2.7	34.8	8.48	2.6
35	0	8.14	1.50	10.5	28.2	5.14	7.5
"	2	6.51	1.58	12.6	28.6	6.32	7.9
36	0	6.26	1.84	11.0	27.4	5.15	6.7
"	2	8.03	1.72	7.9	28.1	8.79	6.0
37	0	9.30	1.38	12.7	27.8	8.46	10.8
"	2	9.25	1.93	10.5	31.8	7.10	8.1
38	0	7.95	1.59	10.2	23.6	4.71	9.8
"	2	6.43	1.74	12.4	28.0	8.07	7.1

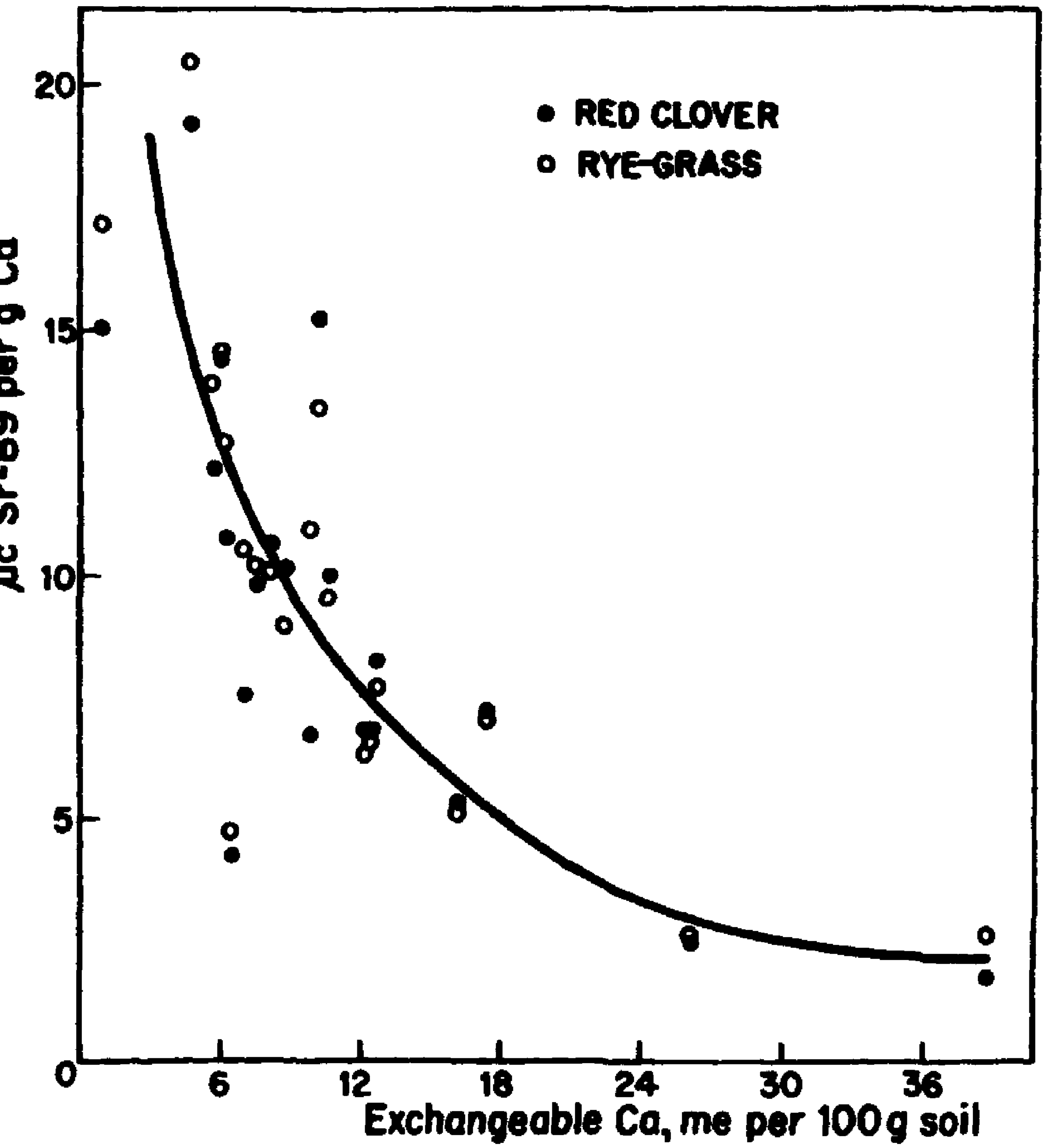

Fig. 4. Strontium-89 to calcium ratios in rye-grass and red clover grown on 20 different soils.

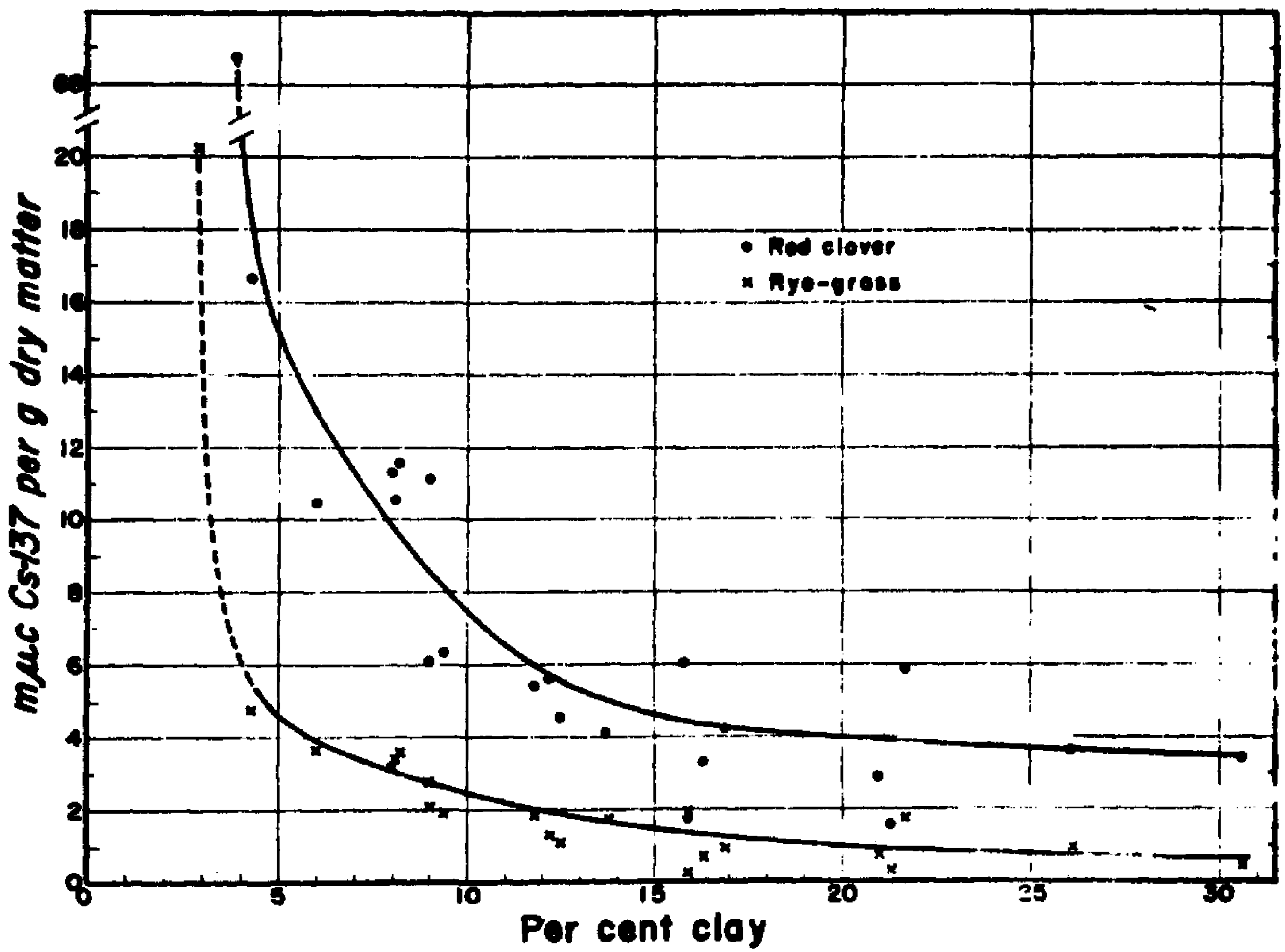

Fig. 5. Caesium-137 concentrations in dry matter of rye-grass and red clover grown on 22 different soils.

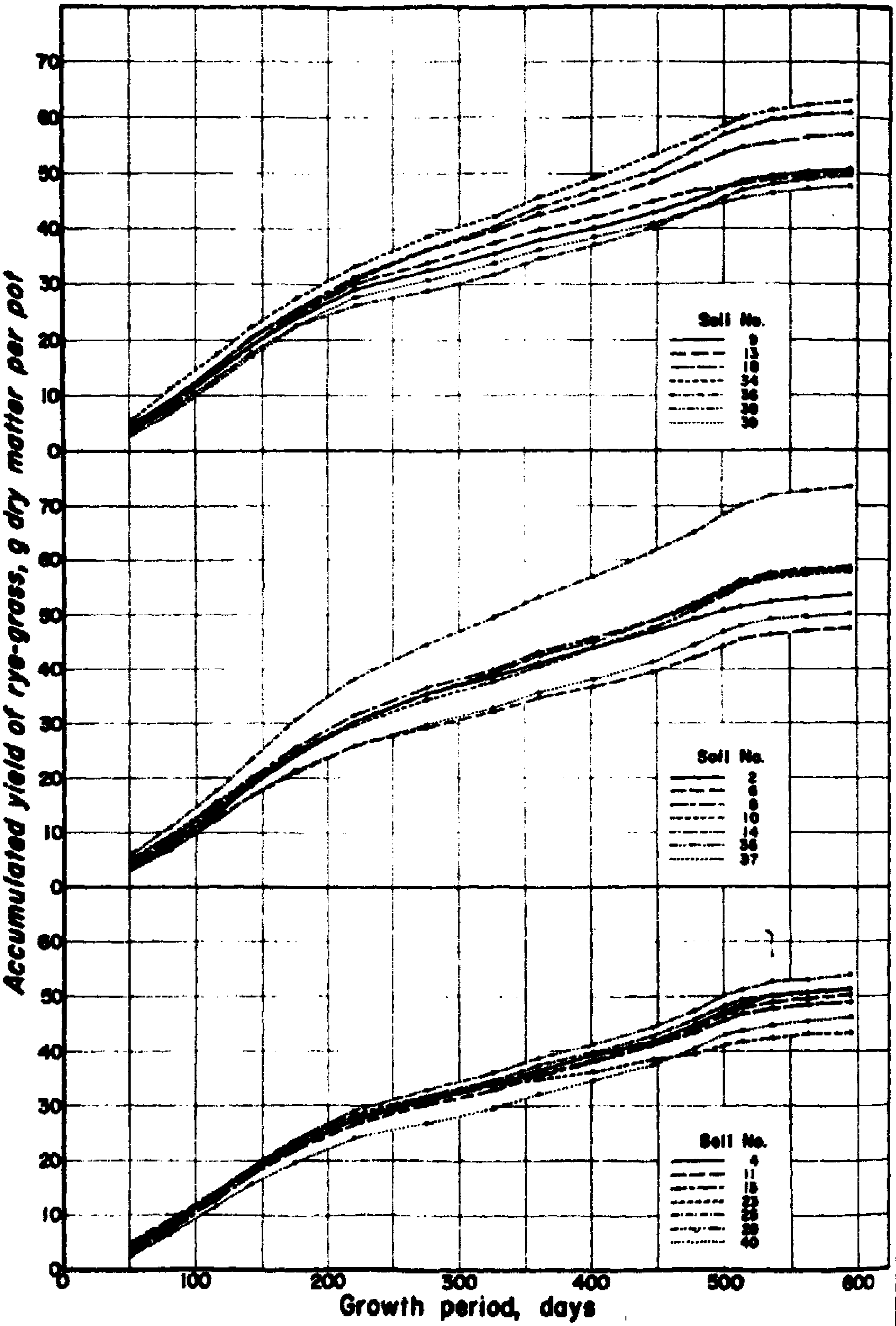

Fig. 6. Accumulated yields of dry matter in rye-grass grown on different soils in a long-term pot experiment.

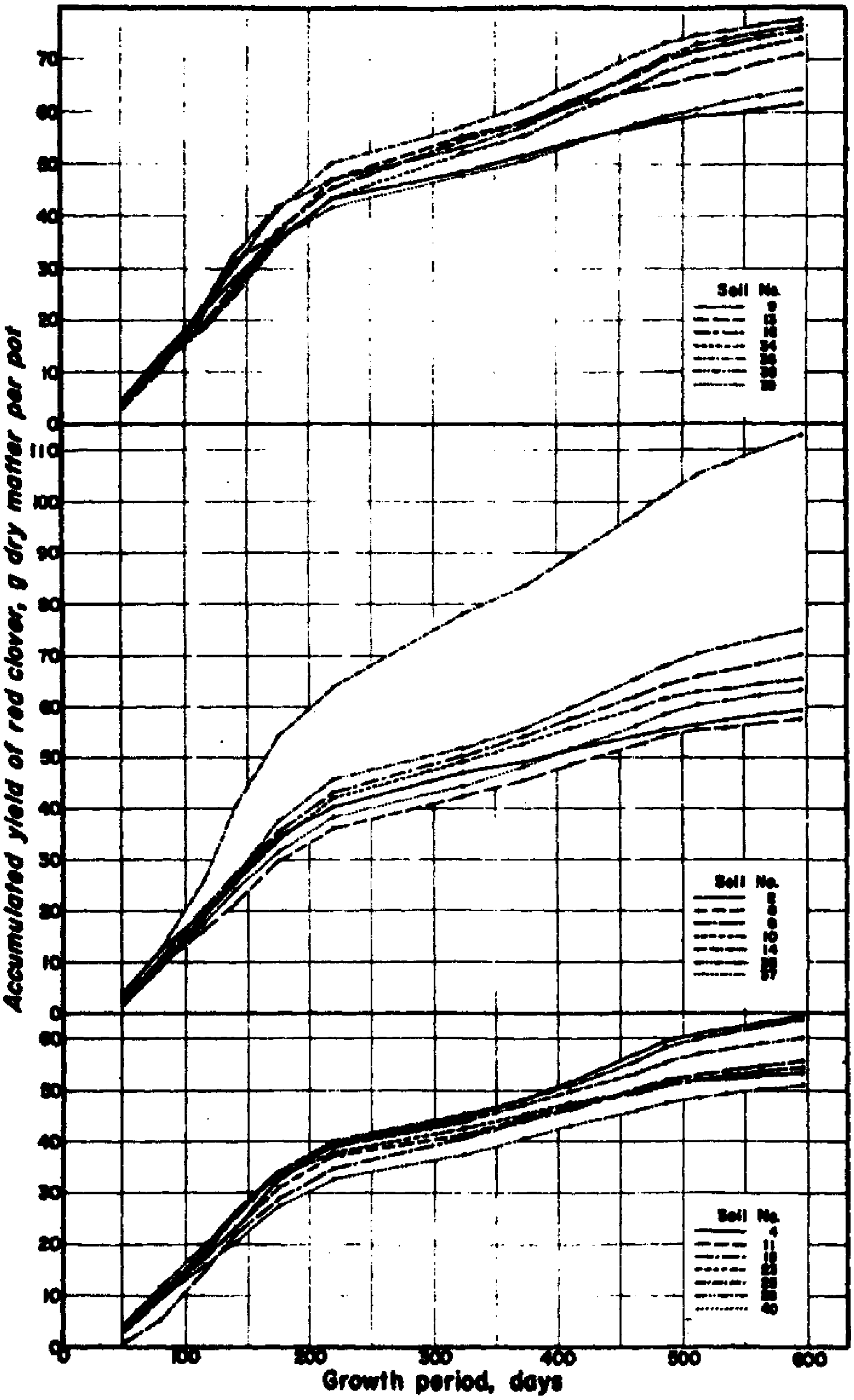

Fig. 7. Accumulated yields of dry matter in red clover grown on different soils in a long-term pot experiment.

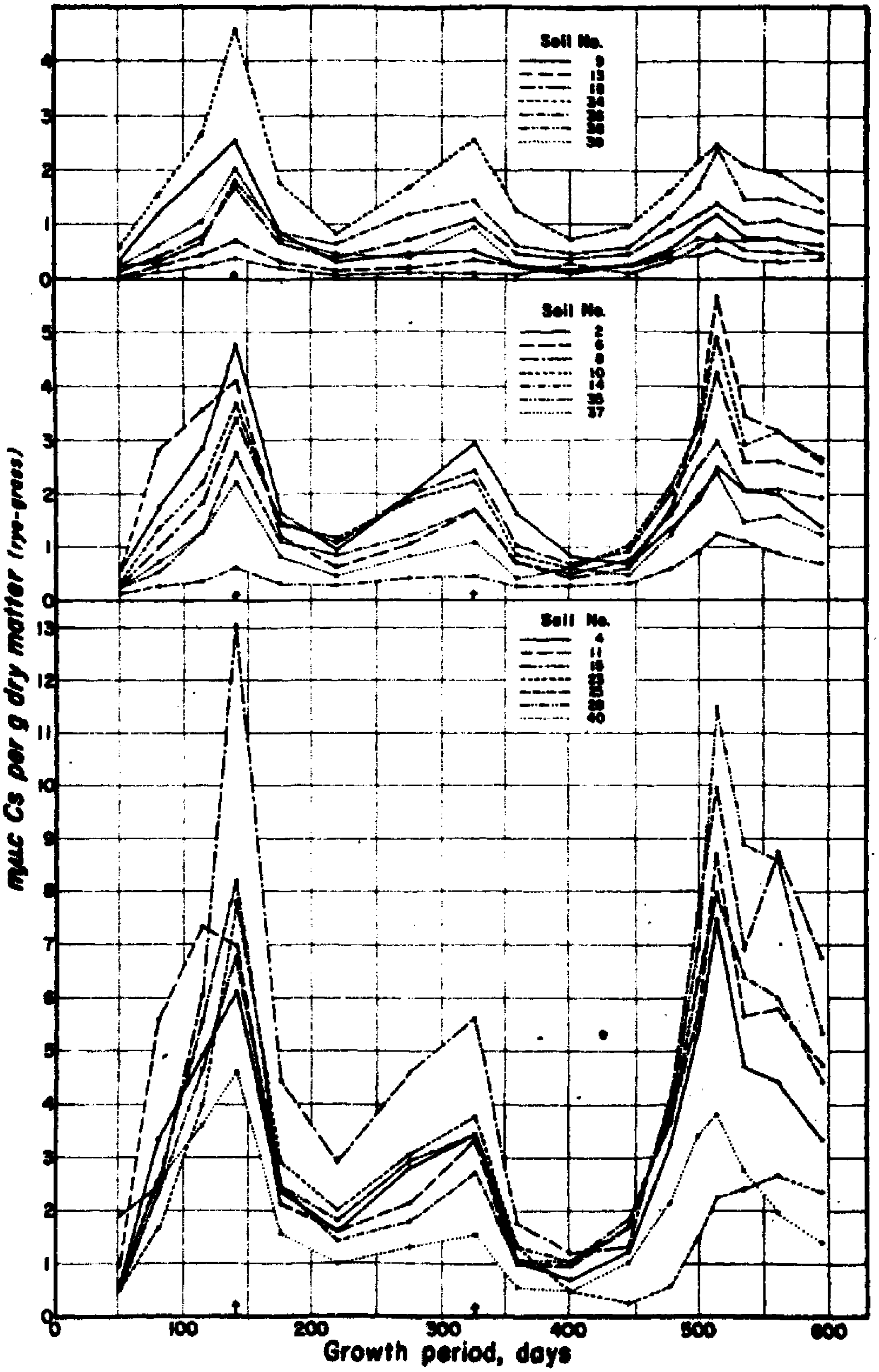

Fig. 8. Variation in caesium-137 concentration in dry matter of rye-grass during a long-term pot experiment with different soils. Potassium nitrate added at points indicated by arrows.

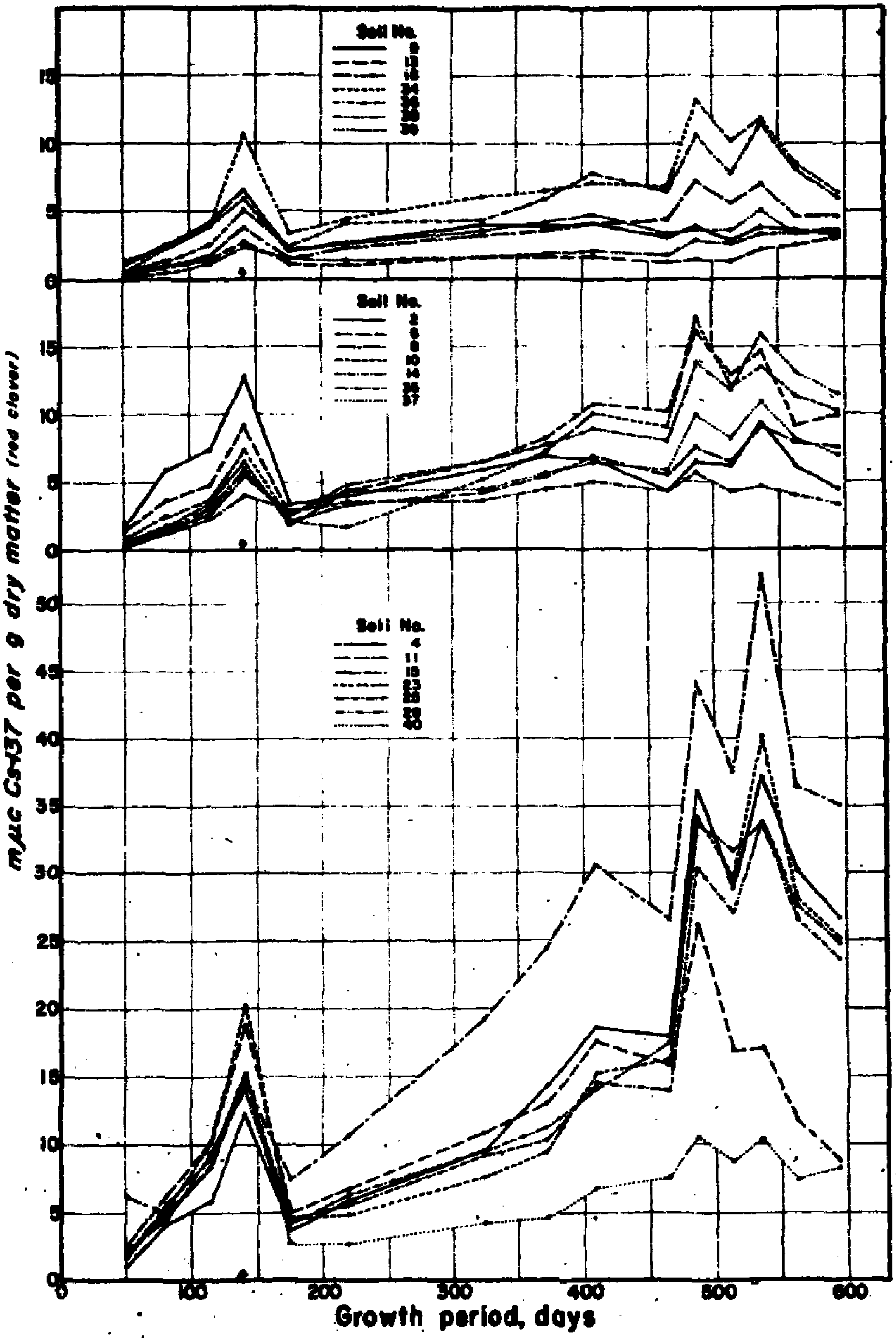

Fig. 9. Variation in caesium-137 concentration in dry matter of red clover during a long-term pot experiment with different soils. Potassium nitrate added at the point indicated by an arrow.

Table 7

Total dry-matter production and Cs-137 uptake by rye-grass (17. cut) and red clover (15. cut) grown in pot experiment with 22 soils (10 μc carrierfree Cs-137 per kg soil)

Soil no.	Rye-grass			Red clover		
	Dry matter	Cs-137 uptake		Dry matter	Cs-137 uptake	
	g/pot	mμc/pot	mμc/g d.m.	g/pot	mμc/pot	mμc/g d.m.
2	53.6	104.0	1.94	59.4	360.3	6.07
4	51.2	159.0	3.11	64.5	729.9	11.32
6	47.6	94.1	1.98	57.8	366.1	6.33
8	59.0	102.3	1.73	70.2	289.3	4.12
9	50.6	45.8	0.91	61.7	222.8	3.61
10	58.1	106.5	1.83	65.6	355.5	5.42
11	50.2	183.7	3.66	53.7	559.0	10.41
13	51.2	16.3	0.32	71.5	113.4	1.59
14	73.7	31.7	0.43	113.0	384.6	3.40
15	48.9	231.2	4.73	55.8	930.9	16.68
18	56.9	41.3	0.73	76.0	220.2	2.90
23	43.5	120.7	2.77	54.7	607.8	11.11
25	51.3	172.9	3.37	60.1	634.1	10.55
28	53.9	190.1	3.53	64.0	740.6	11.57
29	35.1	710.6	20.24	31.4	2159.0	68.75
34	62.7	112.3	1.79	74.1	433.9	5.86
35	58.4	76.2	1.30	75.1	423.7	5.64
36	60.7	56.8	0.94	73.3	329.7	4.21
37	50.4	51.6	1.02	63.3	289.7	4.58
38	49.7	11.5	0.23	76.9	132.5	1.72
39	47.5	33.2	0.70	64.8	214.3	3.31
40	46.3	97.2	2.10	51.0	313.6	6.15

Table 8

Influence of carrier Cs and addition of Cs-137 on the dry-matter production (total of 8 successive cuttings) and Cs-137 uptake by rye-grass grown in pot experiment with 21 soils (10 µc Cs-137 per kg soil)

Soil no.	Dry matter, g/pot			Cs-137 uptake, m c/pot			Cs-137 uptake, m µc/g d.m.		
	1	2	3	1	2	3	1	2	3
2	38.6	38.9	38.5	83.6	81.9	79.0	2.17	2.10	2.05
4	33.9	34.0	33.9	107.1	137.7	122.9	3.15	4.05	3.63
6	32.2	31.6	32.9	64.2	67.1	82.4	1.99	2.12	2.51
8	39.8	40.0	39.0	66.6	83.5	72.0	1.67	2.09	1.85
9	35.5	35.8	36.2	38.2	47.8	47.2	1.08	1.33	1.33
10	37.8	37.4	37.9	66.6	61.9	76.1	1.76	1.65	2.01
11	33.0	32.2	33.6	124.6	134.9	133.0	3.78	4.19	3.96
13	37.3	35.4	38.1	12.4	13.5	14.8	0.33	0.38	0.39
14	39.4	49.6	49.4	17.7	18.1	18.2	0.36	0.37	0.37
15	33.8	34.1	33.8	166.8	203.2	199.1	4.93	5.95	5.89
18	39.8	40.7	39.2	29.1	36.3	32.9	0.73	0.89	0.84
23	33.2	33.4	32.4	108.5	124.5	111.3	3.27	3.74	3.44
25	34.4	34.5	35.0	113.6	125.1	119.2	3.30	3.62	3.41
28	36.0	35.2	36.1	113.5	115.0	112.0	3.15	3.26	3.10
29	26.6	26.4	26.3	670.1	894.6	960.2	25.19	33.87	36.48
35	39.2	39.7	38.9	48.7	67.8	69.7	1.24	1.71	1.79
36	40.5	41.2	40.2	35.7	46.8	40.4	0.88	1.14	1.00
37	32.8	32.7	32.8	32.8	38.4	37.4	1.00	1.18	1.14
38	31.9	32.8	32.0	5.82	6.86	7.49	0.18	0.21	0.23
39	32.8	34.5	33.7	28.0	34.2	30.1	0.85	0.99	0.89
40	29.6	29.9	29.3	68.3	65.0	73.0	2.31	2.17	2.50

Table 9

Influence of added KNO_3, $Ca(NO_3)_2$ and $Mg(NO_3)_2$ on the Cs-137 uptake by rye-grass grown in pot experiment with 21 soils. The difference between the 8th and the 9th crop is caused by (1) KNO_3, (2) $Ca(NO_3)_2$ and (3) $Mg(NO_3)_2$. (10 μc Cs-137 per kg soil)

Soil no.	8th cut, mμc Cs-137/g d.m.			9th cut, mμc Cs-137/g d.m.		
	1	2	3	1	2	3
2	2.95	2.82	2.90	1.61	3.81	3.44
4	3.43	4.79	4.26	1.06	4.24	4.00
6	1.67	2.20	2.53	0.70	2.08	2.13
8	2.43	3.16	2.74	1.03	2.70	2.31
9	0.53	0.64	0.84	0.21	0.62	0.72
10	2.22	1.84	2.68	0.82	1.74	1.92
11	3.31	4.20	3.88	1.01	3.44	3.59
13	0.36	0.30	0.36	0.22	0.42	0.47
14	0.47	0.47	0.38	0.26	0.49	0.43
15	5.64	5.71	7.04	1.78	6.69	6.18
18	1.12	1.24	1.48	0.48	1.21	1.28
23	3.74	4.12	3.59	1.34	4.36	4.12
25	2.71	3.15	3.64	1.08	3.30	3.32
28	3.41	3.53	3.56	1.33	3.00	3.49
29	30.96	31.27	32.67	11.72	47.04	46.02
35	1.68	2.22	2.35	0.72	1.96	1.63
36	1.45	1.48	1.63	0.63	1.22	1.47
37	1.09	1.34	1.28	0.43	1.15	1.20
38	0.09	0.16	0.15	0.06	0.17	0.19
39	0.97	0.68	0.67	0.24	0.66	0.61
40	1.54	1.74	3.33	0.56	1.47	2.02

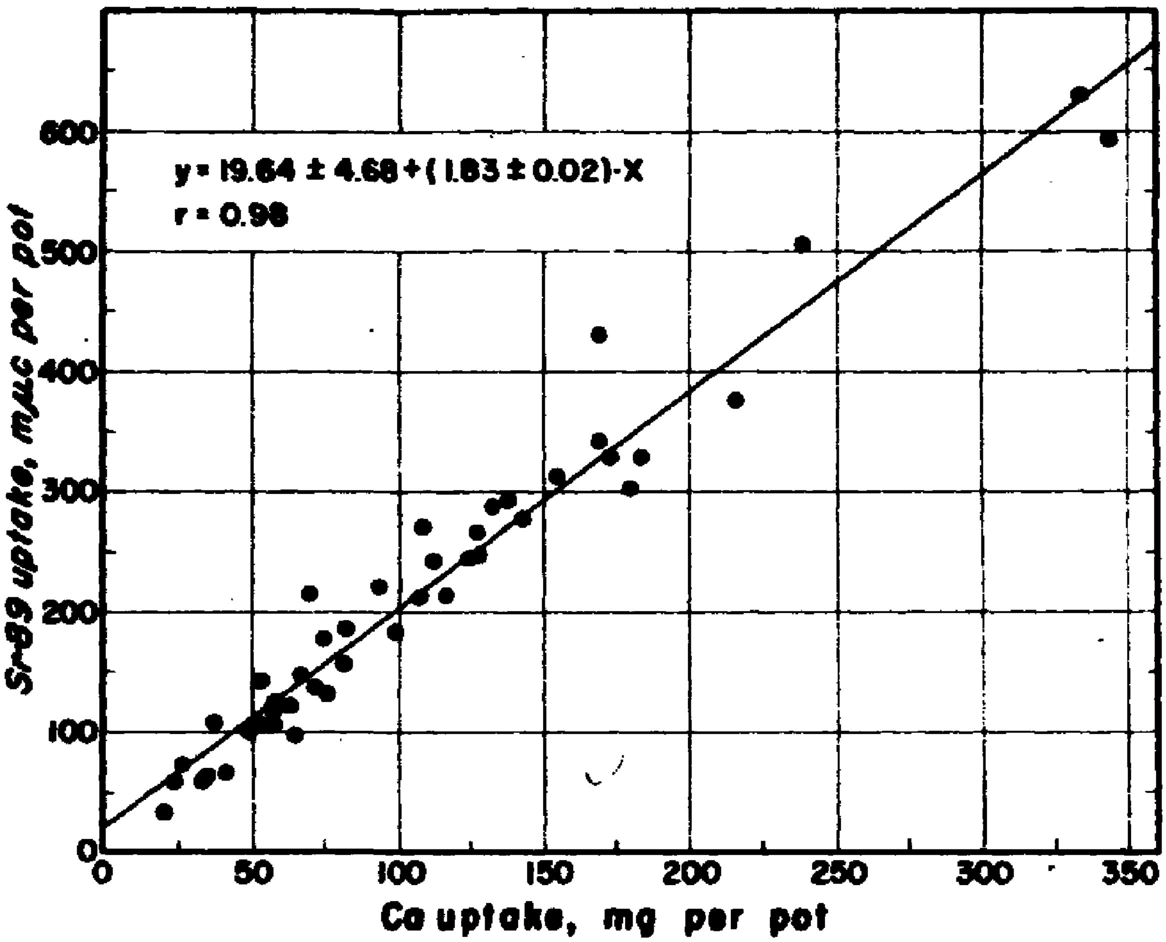

Fig. 1. Relationships between strontium-89 and calcium uptake by forty-four plant species grown in a pot experiment (3 μc carrierfree Sr-89 per pot).

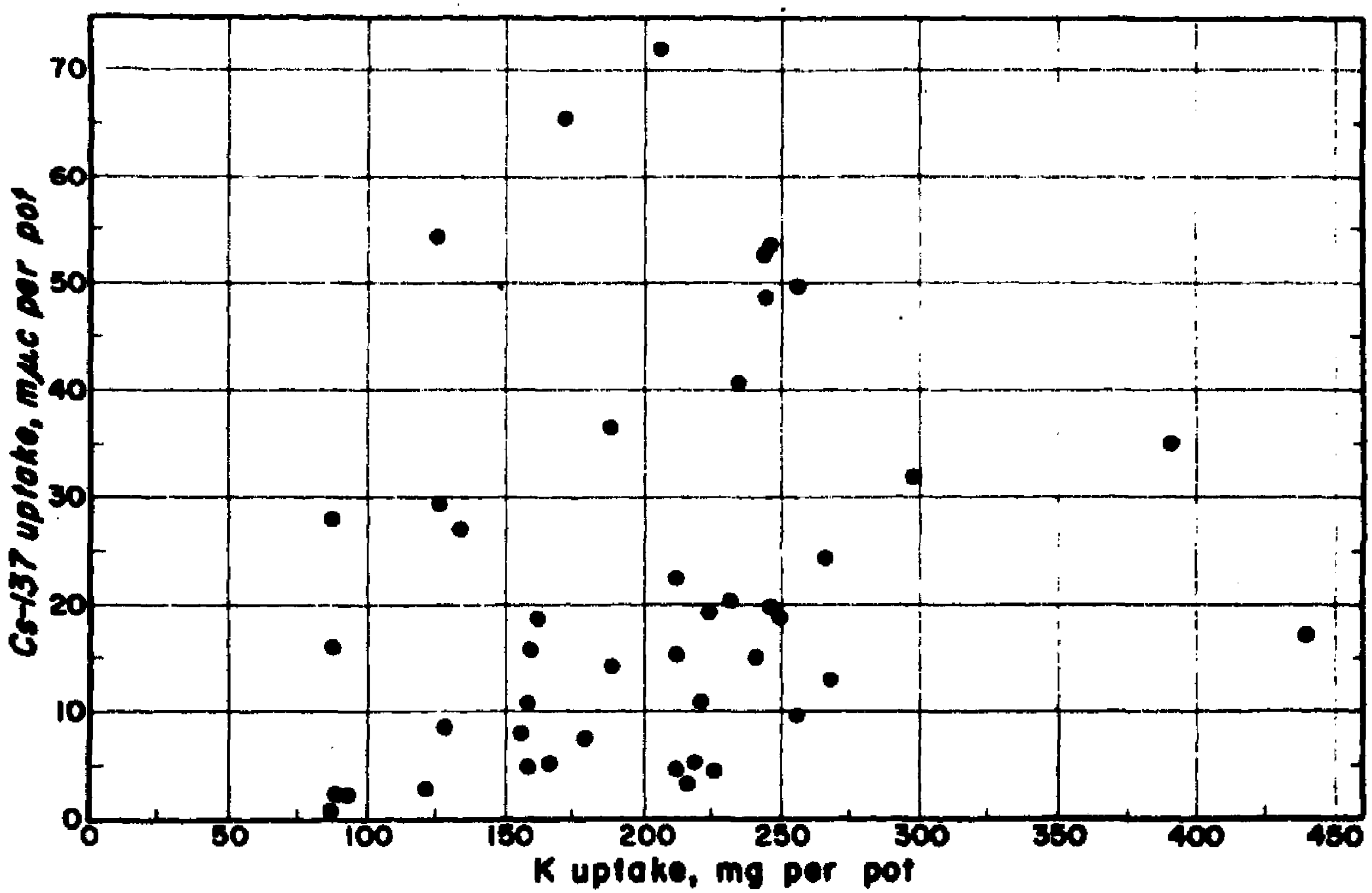

Fig. 2. Relationships between caesium-137 and potassium uptake by forty-four plant species grown in a pot experiment (10 μc carrierfree Cs-137 per pot).

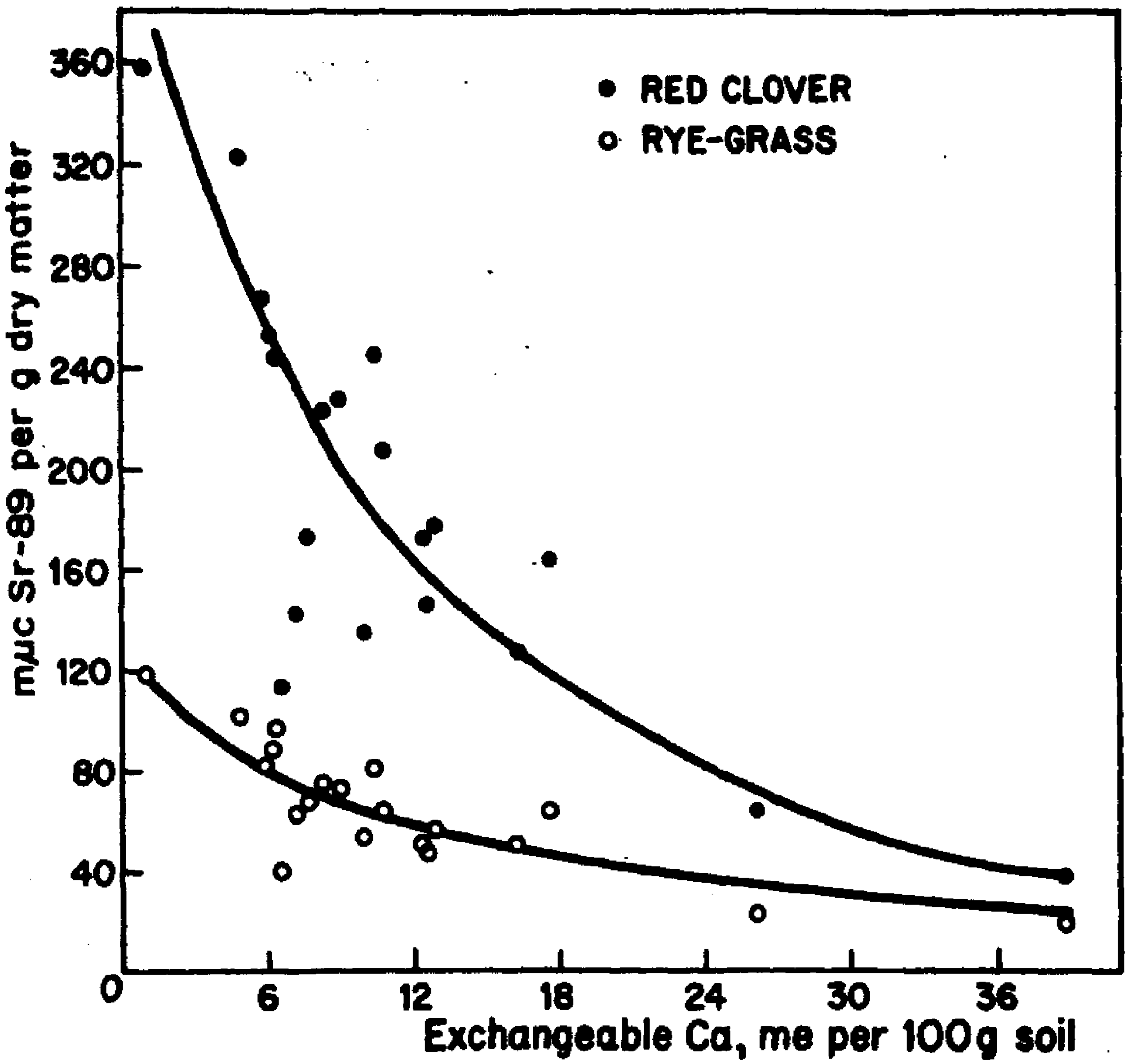

Fig. 3. Strontium-89 concentrations in dry matter of rye-grass and red clover grown on 20 different soils.

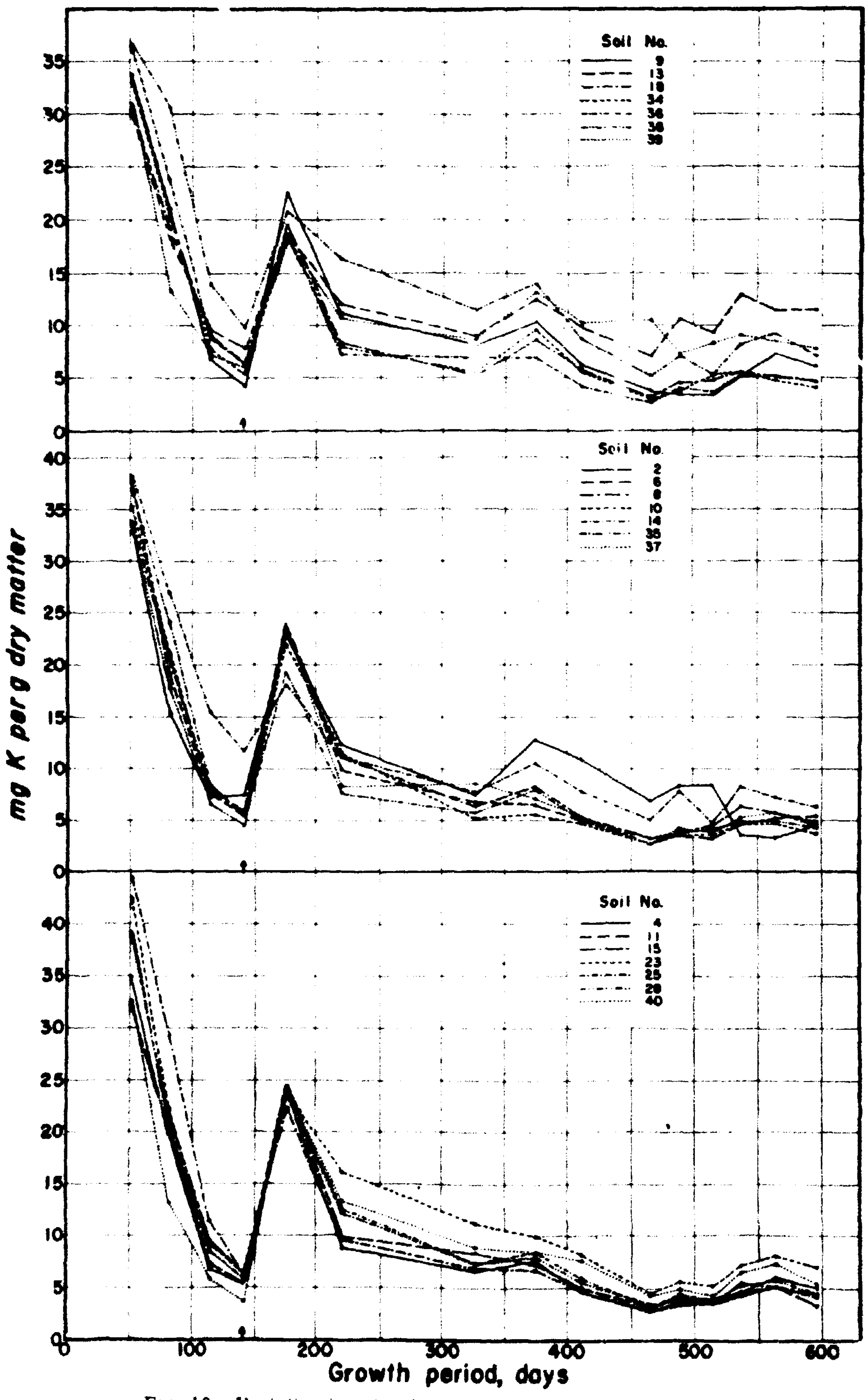

Fig. 10. Variation in potassium concentration in dry matter of red clover during a long-term pot experiment with different soils. Potassium nitrate added at the point indicated by an arrow.